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High-sensitivity and low-noise GaN-based ultraviolet photodetectors

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Abstract. This study presents the fabrication of ultraviolet metal-semiconductor-metal photodetectors based on ultrathin epitaxial layers GaN grown on sapphire substrates. The devices were characterized through current-voltage measurements and sensitivity and noise characteristics calculations. At a bias voltage of 1 V, the PDs demonstrated a responsivity of 156 $mA \cdot W^{-1}$ and a noise-equivalent power of $0.4 \cdot 10^{-22}$ $W \cdot Hz^{-0.5}$, which highlight their high-sensitivity and low-noise performance.

Keywords: ultraviolet photodetector, GaN, metal-semiconductor-metal

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Высокочувствительные и малошумящие ультрафиолетовые фотодетекторы на основе GaN

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Аннотация. В настоящей работе представлены ультрафиолетовые фотодетекторы типа металл-полупроводник-металл на основе ультратонких эпитаксиальных слоев GaN, выращенных на подложках c-Al_2O_3. Вольт-амперные характеристики устройств были исследованы в темноте и при ультрафиолетовом освещении, в результате чего были определены их чувствительность и эквивалентная мощность шума – 156 $мА \cdot Вт^{-1}$ и $0.4 \cdot 10^{-22}$ $Вт \cdot Гц^{-0.5}$ соответственно при напряжении 1 В.

Ключевые слова: ультрафиолетовый фотодетектор, GaN, металл-полупроводник-металл

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Introduction

Ultraviolet photodetectors (UV PDs) are critical components in a wide array of applications, including environmental monitoring, flame detection, medicine and optical communication systems [1]. In addition, there is a growing demand for high-performance UV sensors that can combine high sensitivity and low noise.

Among many materials, GaN has emerged as a leading candidate for fabricating these devices due to wide bandgap (~3.4 eV), which provides UV selectivity without expensive optical filters, as well as its exceptional thermal stability, radiation resistance, and high electron mobility [2]. These properties of GaN make this semiconductor an excellent alternative to silicon, the detectors based on which have low UV sensitivity and degrade under prolonged exposure to UV radiation.

There are various types of PDs designs, but the most attractive ones are metal-semiconductor-metal (MSM) PDs, which offer high speed and sensitivity as well as ease of fabrication [3]. In this article, high-sensitivity and low-noise UV MSM PDs fabricated on ultrathin GaN epitaxial layers are presented.

Materials and Methods

GaN epitaxial layers were synthesized by plasma-assisted molecular beam epitaxy (PA MBE) using Veeco GEN 200 industrial type MBE setup on sapphire (c-Al_2O_3) substrates. The surface morphology of the synthesized samples was characterized using a scanning electron microscope (SEM) Supra 25 Zeiss. The electrical properties of the GaN epitaxial layers, including conductivity type and concentration of charge carriers in the GaN epitaxial layers were assessed using Hall effect measurements based on the Van der Pauw four-point probe method using the Ecopia HMS-3000 system.

MSM PDs with Ni/Au semitransparent interdigitated electrodes were fabricated on the grown layers using standard laser lithography technique, e-beam and thermal vacuum evaporation. Lithography was carried out on a Heidelberg DWL 66FS setup, metal sputtering was performed on an BOC Edwards Auto 500 system. The thickness of the metallization was determined using an Ambios XP-1 profilometer.

The current-voltage (I–V) characteristics of the formed PDs were measured in the dark and under UV illumination with a wavelength of 365 nm using Agilent B1500A semiconductor device parameter analyzer.

Results and discussion

The 200 nm GaN layer grown on the sapphire substrate exhibits a labyrinth-like surface morphology (Fig. 1, *a*, *b*). This structure is probably a result of the Volmer–Weber growth mode [4], driven by elastic stress arising from the significant lattice mismatch between GaN and c-Al_2O_3 (~16%). It is important to note that the rough surface morphology can potentially provide more efficient absorption of incident photons and lead to an increase in PDs responsivity compared to devices based on smooth layers.

Hall effect measurements confirmed n-type conductivity of undoped GaN epitaxial layers with a carrier concentration of $6.4\cdot10^{18}$ cm^{-3}. Such a high value can be associated with the three-dimensional MBE growth of GaN layers and with a large number of defects in them.

Fig. 1, *c* shows PDs with semitransparent Ni/Au (5/10 nm) interdigitated electrodes fabricated on synthesized ultrathin GaN epitaxial layers.

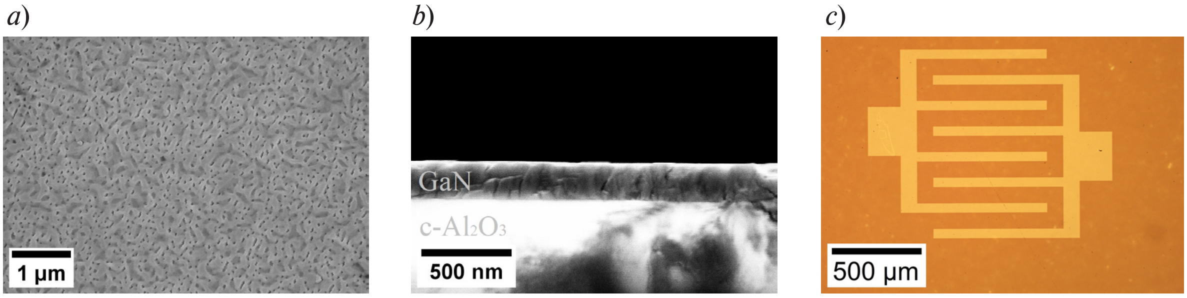

Fig. 1. SEM images of the GaN/*c*-Al_2O_3 epitaxial structure: cross-section (*a*) and plan view (*b*), optical image of the PDs (*c*)

During *I*—*V* measurements, it was observed that exposure to UV radiation leads to an increase in device current (Fig. 2, *a*). In addition, the PDs exhibit a relatively low dark current (0.02 mA at 1 V bias). The highest value of the photocurrent to dark current ratio (which determines the noise characteristics of the devices) was observed at low voltages (at 0.05 V) and was 39, at higher voltages this ratio was greater than 1.

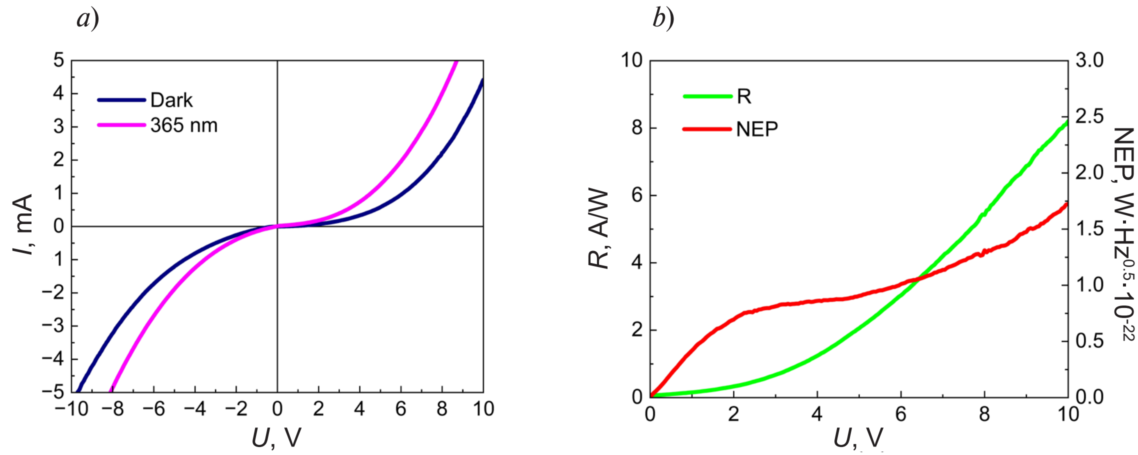

Fig. 2. *I*—*V* characteristics (*a*) and voltage dependence of photoresponse and NEP (*b*) of the formed PDs

In addition, the device performance was evaluated by determining responsivity (*R*) [5]:

$$R = \frac{I_{365nm} - I_d}{P_{opt}} = \frac{I_{ph}}{P_d \cdot A}, \tag{1}$$

where I_{365nm} the current measured upon UV illumination, I_d is the dark current, I_{ph} is the photocurrent, P_{opt} is the optical power, P_d is the power density and A is the active area of the device. Also, noise equivalent power (NEP) of the fabricated devices was calculated using the following equation [5]:

$$\text{NEP} = \frac{\sqrt{2eI_d}}{R}, \tag{2}$$

where e is electron charge. The responsivity and NEP values at 1 V for the PDs were 156 $mA \cdot W^{-1}$ and $0.4 \cdot 10^{-22}$ $W \cdot Hz^{-0.5}$. These results are comparable to PDs based on thin nanostructured GaN epitaxial layers reported in literature [6]. As noted above, the high responsivity value can be associated with the rough surface morphology, providing a large area of interaction of photons with the semiconductor. This could also provide a low value of the NEP. Thus, in this work, high-sensitivity and low-noise UV MSM PDs based on ultrathin GaN were demonstrated.

Conclusion

In this work, UV high-sensitivity and low-noise PDs based on the GaN/*c*-Al_2O_3 were demonstrated. It was found that the fabricated devices have a responsivity and noise equivalent power equal to 156 $mA \cdot W^{-1}$ and $0.4 \cdot 10^{-22}$ $W \cdot Hz^{-0.5}$ at 1 V respectively. These results contribute to the development of high-performance GaN-based UV PDs.

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